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## TIME-DEPENDENT RESPONSE OF MI SiC/SiC COMPOSITES PART 2: SAMPLES WITH HOLES (PREPRINT)

G. Ojard, R. Miller, Y. Gowayed, J. Chen, U. Santhosh, J. Ahmad, and R. John

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**14. ABSTRACT**

Time-dependent response of samples with holes manufactured from MI SiC/SiC composites (01/01 material) was experimentally evaluated under creep and dwell fatigue loading. Forty specimens with a central hole with sizes 2.286, 4.572 and 6.35 mm were tested. All specimens showed primary and steady state creep responses. Environmental degradation was empirically related to material response at different stress levels utilizing information from samples without holes. ANSYS Finite Element Analysis was used to map the creep strain in the vicinity of the hole utilizing the empirical correlation.

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# TIME-DEPENDENT RESPONSE OF MI SIC/SIC COMPOSITES PART 2: SAMPLES WITH HOLES

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## ABSTRACT

Time-dependent response of samples with holes manufactured from MI SiC/SiC composites (01/01 material) was experimentally evaluated under creep and dwell fatigue loading. Forty specimens with a central hole with sizes 2.286, 4.572 and 6.35 mm were tested. All specimens showed primary and steady state creep responses. Environmental degradation was empirically related to material response at different stress levels utilizing information from samples without holes. ANSYS Finite Element Analysis was used to map the creep strain in the vicinity of the hole utilizing the empirical correlation.

## INTRODUCTION

Testing is conducted to understand the behavior of Ceramic Matrix Composites (CMCs) under conditions of sustained load at high temperatures. Examples of long term environments would include ground base turbines for power generation where CMCs are being considered for combustor liners, turbine vanes and shroud applications. These applications can see design times of up to 30,000 hours. Such long term applications are working to leverage the high temperature material capability while taking advantage of the weight reduction, reduced cooling and durability improvements that CMCs can provide over typical metals.

As part of an effort to look into the long-term behavior of a CMC, a series of creep and dwell fatigue tests were undertaken for specimens with and without a central hole at 1204 <sup>o</sup>C and various stress levels. This paper reports data and analysis of specimens with holes. Data on specimens without holes can be found in part 1 of this series of papers.

## EXPERIMENTAL PROGRAM
*Materials and Manufacturing*
The material chosen for the study was the Melt Infiltrated SiC/SiC CMC system, which was initially developed under the Enabling Propulsion Materials Program (EPM) and is still under further refinement at NASA-Glenn Research Center (GRC).  This material system has been systematically studied at various development periods and the most promising was the 01/01 Melt Infiltrated iBN SiC/SiC (01/01 is indicative of the month and year that development was frozen). There is a wide set of data from NASA for this system as well as a broad historic database from the material development.  This allowed a testing system to be put into place to look for key development properties which would be needed from a modeling effort and would hence leverage existing data generated by NASA-GRC.

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The Sylramic® fiber was fabricated by DuPont as a 10 μm diameter stochiometric SiC fiber and bundled into tows of 800 fibers each. The sizing applied was polyvinyl alcohol (PVA). For this study, the four lots of fibers, which were used, were wound on 19 different spools. The tow spools were then woven into a 5HS balanced weave at 20 EPI. An in-situ Boron Nitride (iBN) treatment was performed on the weave (at NASA-GRC), which created a fine layer of BN on every fiber. The fabric was then laid in graphite tooling to correspond to the final part design (flat plates for this experimental program). All the panels were manufactured from a symmetric cross ply laminate using a total of 8 plies. The graphite tooling has holes to allow the CVI deposition to occur. At this stage, another BN coat layer was applied. This BN coating was doped with Si to provide better environmental protection of the interface. This was followed by SiC vapor deposition around the tows. Typically, densification is done to about 30% open porosity. SiC particulates are then slurry cast into the material followed by melt infiltration of a Si alloy to arrive at a nearly full density material. The material at this time has less than 2% open porosity. Through this process, 15 panels were fabricated in 3 lots of material.

After fabrication, all the panels were interrogated by pulse echo ultrasound (10 MHz) and film X-ray. There was no indication of any delamination and no large scale porosity was noted in the panels. In addition, each panel had two tensile bars extracted for witness testing at room temperature. All samples tested failed above a 0.3% strain to failure requirement. Hence, all panels were accepted into the testing effort.

*Creep testing at 1204 ºC*
Creep testing is a test to determine the strain-time dependence of a material under a constant load. This test is also used to determine the long-term behavior of the material under combination of load and temperature. For ceramic matrix composites, when this testing is done in air, there is an added complexity of environmental exposure. Creep testing has three regimes, primary (or initial), secondary (steady state) and tertiary creep. The creep rate for the material is typically measured during the secondary (steady state) regime.

A total of 12 creep tests were done on straight-sided tensile bars with two different central hole sizes (2.286 and 4.572 mm) at 1204 ºC. The stress-time data for this experiment is summarized in Figure 1. There were no failures in this testing effort. During the creep testing, the creep strain was recorded. Typical creep strain-time data for some of the longer duration samples are shown in Figures 2 and 3 for 2.286 and 4.572 mm holes, respectively.
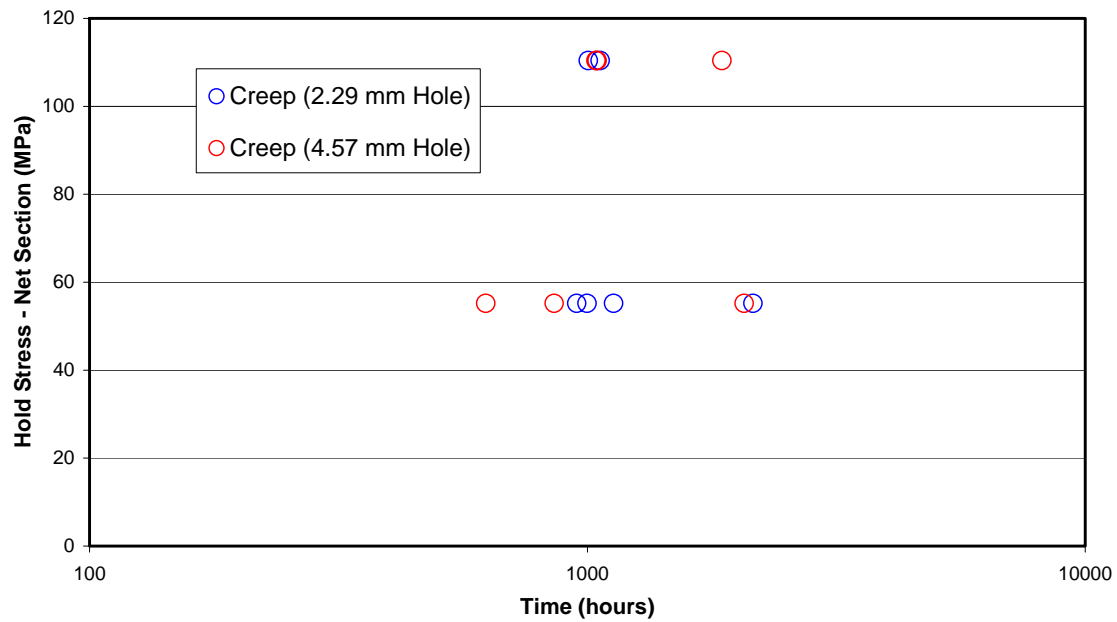
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Figure 1: Net Section Stress-Time data for creep testing of samples with holes
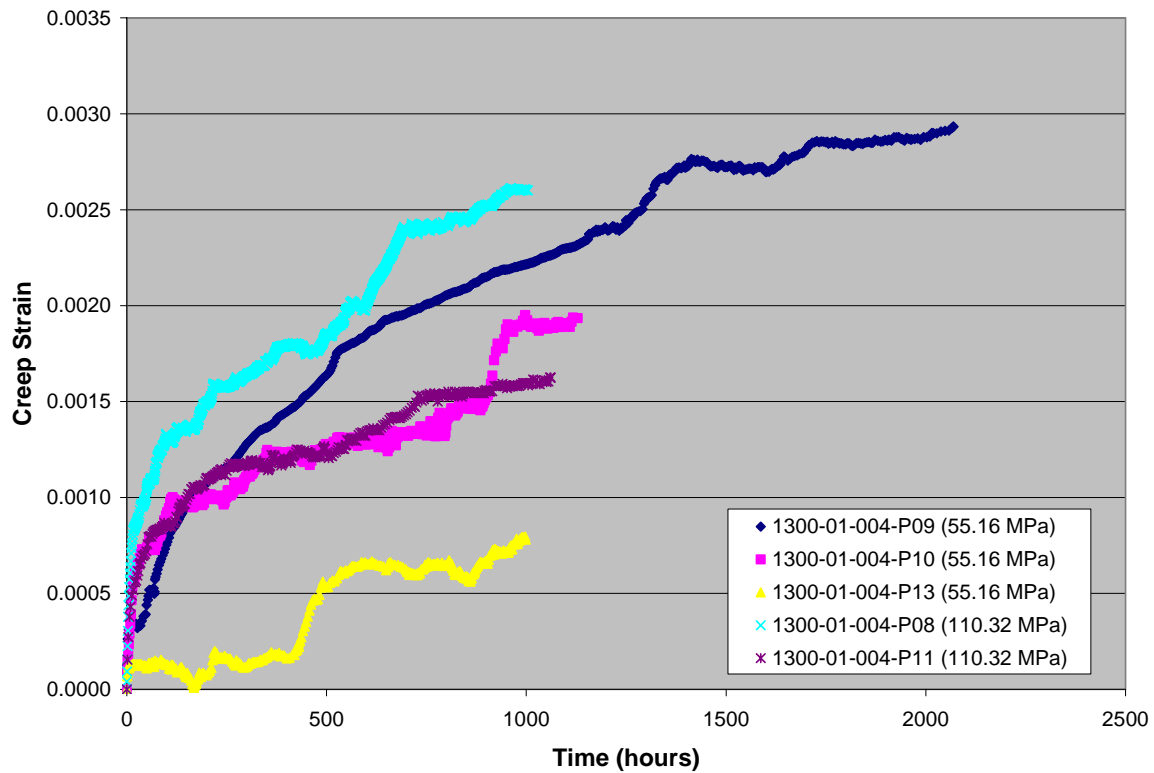


Figure 2: Creep strain vs. time for specimens with 2.286 mm hole

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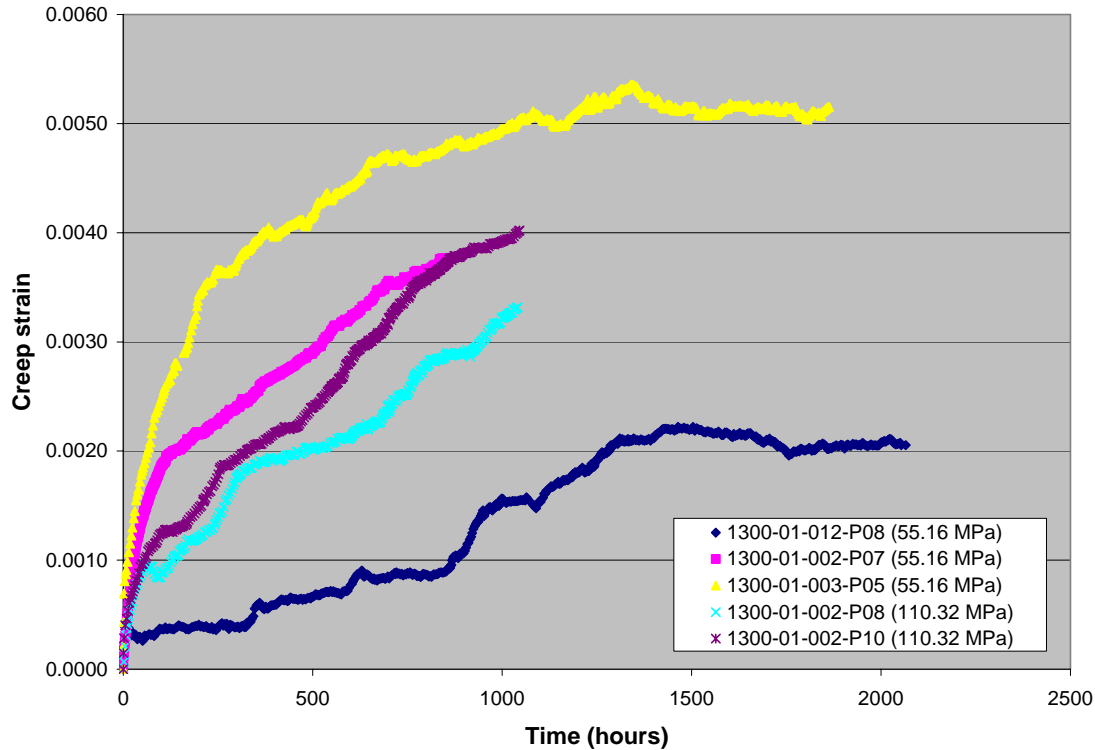Daytona Beach, Florida, USA, January 21-26, 2007



Figure 3: creep strain vs. time for specimens with 4.572 mm hole

The average slopes of the steady state region of the 2.286 and 4.572 mm holes and no hole specimens are listed in Table 1 along with the standard deviation values. It can be seen that the standard deviation value is high as compared to the average value for some of the experiments, especially the 2.286 mm hole loaded at 55.16 MPa and the 4.572 mm hole at 55.16 MPa. The impact of the increase in the hole radius can be seen from the data of the 4.572 mm hole especially at the high stress level, but the effect of the existence of the 2.286 mm hole is not evident at both stress levels.

Table 1: Average and standard deviation of the slope (/sec) of the steady state region

| Net section stress | Average | Standard deviation |
|---|---|---|
| *No hole* | | |
| 55.16 MPa | --- | --- |
| 110.32 MPa | 3.4xE-10 | 1.3E-10 |
| 2.286 mm *hole* | | |
| 55.16 MPa | 2.62E-10 | 2.05E-10 |
| 110.32 MPa | 3.16E-10 | 1.79E-10 |
| 4.572 mm *hole* | | |
| 55.16MPa | 3.59E-10 | 3.19E-10 |
| 110.32 MPa | 7.46E-10 | 2.02E-10 |

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*Dwell Fatigue at 1204 ºC*

Dwell fatigue testing, sometimes referred to as "low cycle fatigue tests", is the superposition of a stress hold at the peak stress of a fatigue cycle. Dwell fatigue tests were conducted where the dwell time was 2 hours with a 1 minute load and unload at the beginning and end of each cycle. Twenty eight samples were tested at 55.16, 110.32, 165.48 and 193.06 MPa net-section stress levels. Data acquired during these tests are typically large in size and include load-reload tests at different time intervals. A Matlab code was developed to extract this data and allow characterization of the change in strain with time. Figure 4 shows the Matlab code output for the change of total strain with time for samples with 2.286 mm hole.
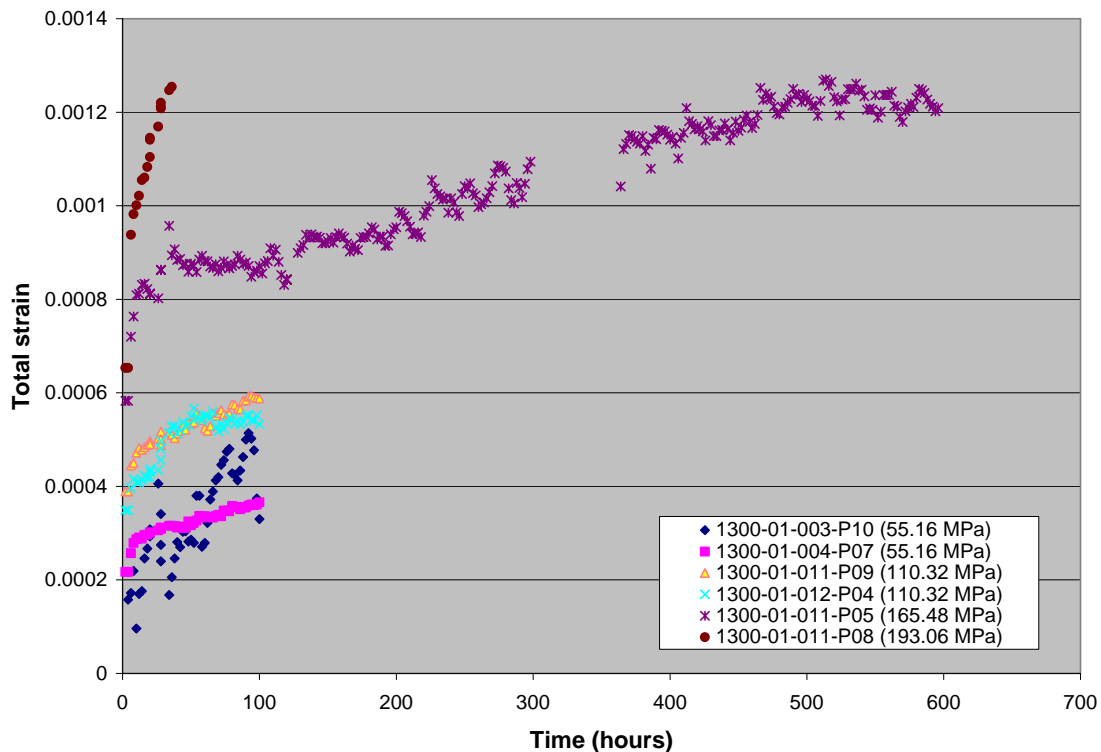


Figure 4: Change in the value of total strain for specimens with 2.286 mm hole with time at 1204 ºC

From Figure 4, it can be seen that the value of the total strain is consistently higher at higher stress levels. The primary creep region was much smaller in size than that observed in creep tests (refer to paper 1 in this series).

*Creep analysis using ANSYS* for samples with a central hole

A 3 parameter curve fitting equation $strain\_creep = A\sigma^n t^p + \varepsilon_o$ (with $A$=2.51e-23, $n$=2.3, $p$=0.30, $\sigma$ = applied remote stress (Pa), t = time (hours), and $\varepsilon_o$ = elastic strain)

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was used to fit the data for the standard dwell fatigue samples and provided a reasonable fit. This equation was used to map the strain for specimens with holes. The existence of the hole causes stress concentrations that alter the strain values in the area close to the hole. In order to develop an understanding of the impact of the existence of the hole on the strain values, ANSYS FEA software was used to model the behavior of the material as an orthotropic material. Element type PLANE 182 was used to generate the 3D model and element type SOLID185 was used to conduct analysis using the mesh shown in Figure 5. The orthotropic creep behavior was represented by the combination of Hill's anisotropy model and the implicit Creep Model 6 in ANSYS. The Hill option's material behavior is described by six constants that define the creep ratios in different directions. The constants were taken as follows: C1(x)=1.0, C2(y)=1.0, C3(z)=1.1, C4(xy)=0.9, C5(yz)=0.9, C6(xz)=0.9.

The change of creep strain with time at four different locations around the hole shown in Figure 6 was reported by ANSYS for undamaged material. It can be seen that the local creep at the edge of the hole is large and may cause local damage. Figure 7 shows the comparison between the measured data and model calculations for 55.16 and 110.32 MPa loaded specimens measured at point 1 with a reasonable level of accuracy.
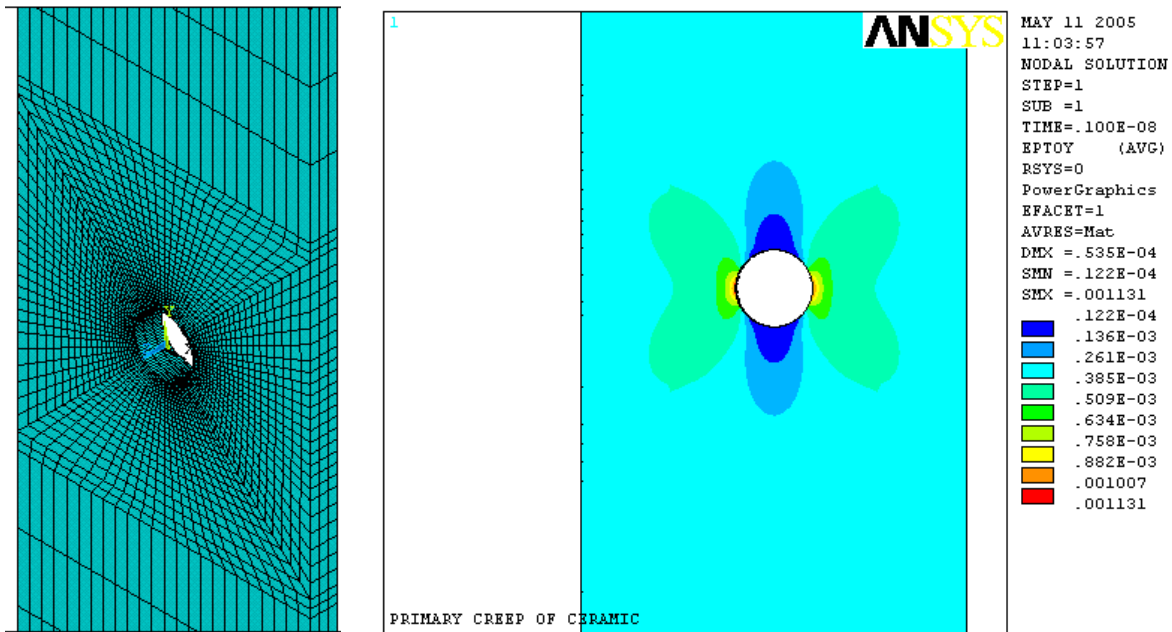


Figure 5: ANSYS creep-strain distribution around the hole at time t=0

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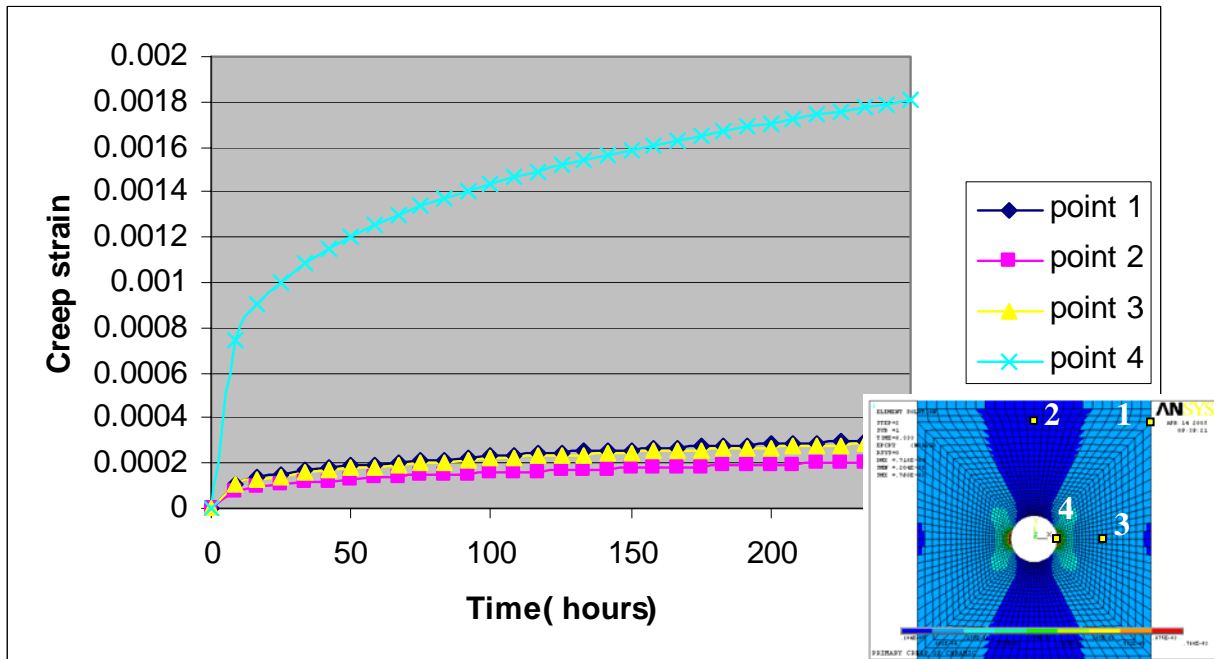Daytona Beach, Florida, USA, January 21-26, 2007

Figure 6: ANSYS creep-strain distribution at t=8.33 h and location of monitoring points
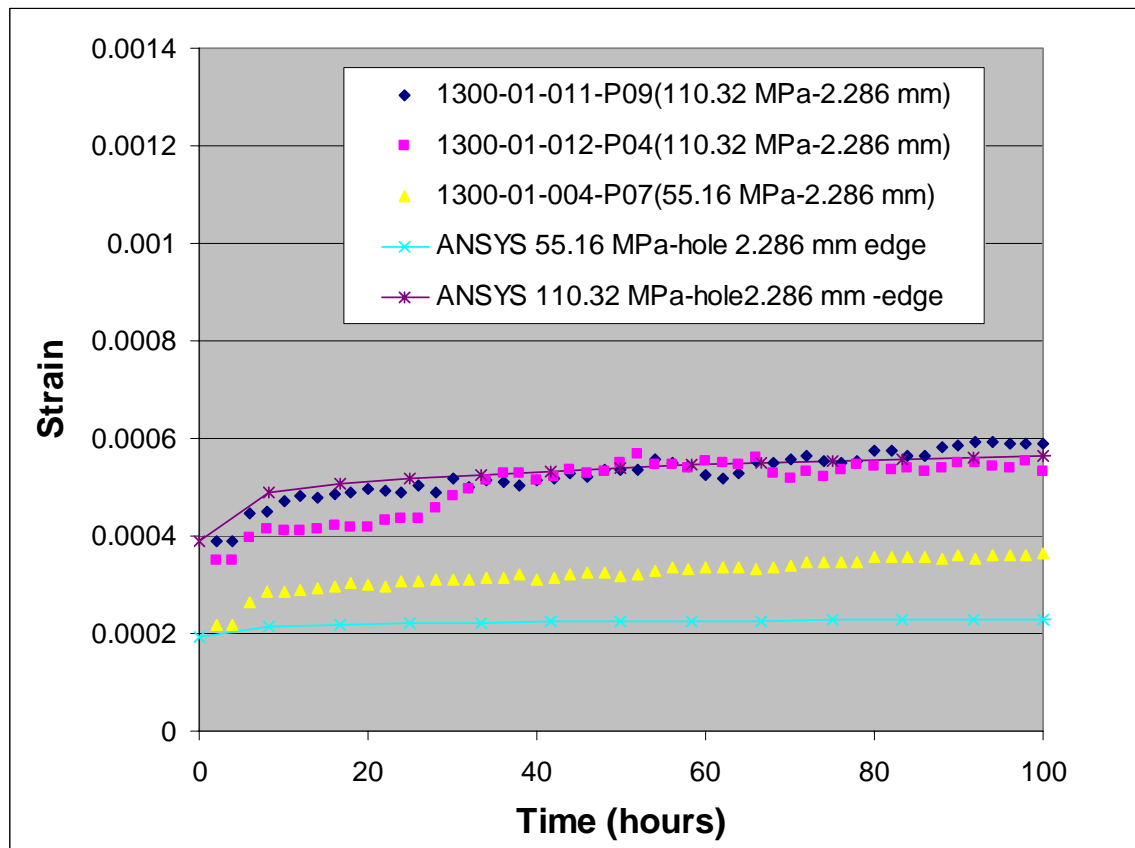


Figure 7: Experimental data and ANSYS results for specimens with 2.286 mm hole

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**Conclusions**

Experimental evaluation of time-dependent response of SiC/SiC composites was conducted utilizing creep and dwell fatigue experiments. Samples had central holes with sizes of 2.286, 4.572 and 6.35 mm forming 20% of the width of the specimen. Data from dwell fatigue experiments were more consistent than those in creep experiments. Dwell fatigue data fit for standard samples without holes were used to model creep strain around holes utilizing ANSYS. The model showed a 9 fold increase in creep strain values in the vicinity of the hole when compared to at the sample edge.

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